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LITERATURE REVIEW ON UNDERFLOOR AIR DISTRIBUTION (UFAD) SYSTEM

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Executive Summary

An extensive literature review about Underfloor Air Distribution (UFAD) systems is presented. For the review, various sources and search engines were used to find the technical research and literature by using specific keywords to search for the relevant reports or browsing through the list of documents. Sources and search engines include ASHRAE abstract archives (1980-1997), Elsevier Literature Search Engine, the Center for the Built Environment (CBE), the Building Diagnostics Research Institute.

An UFAD system is an HVAC system that uses the open space (i.e., the underfloor plenum) between the structural slab and the underside of a raised floor to deliver conditioned air to supply outlets located at or near floor level within the occupied zone. The reported benefits of this system are: 1) improved thermal comfort, 2) reduced energy use, 3) reduced life-cycle building costs, 4) reduced floor-to-floor height in new construction, and 5) improved productivity and health. The barriers in the adoption of UFAD systems are: 1) still new and unfamiliar technology, 2) lack of information and design guidelines, 3) no whole-building simulation program for the system, 4) high initial costs, 5) cold feet and draft discomfort reported in some installed, 6) condensation and dehumidification issues, and 7) spillage and dirt entering the UFAD systems.

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I. INTRODUCTION

1.1. Sources Searched and Keywords

Various sources and search engines were used to find the technical research and literature by using specific keywords to search for the relevant reports or browsing through the list of documents. First, the 227 of references from the book “Underfloor Air Distribution (UFAD) Design Guide” by Fred S. Bauman were used to start searching literature. His references include papers, articles, and web references presenting major contributions to the understanding and development of UFAD technology and design. Other literature search methods were utilized. Below is the list of sources.

ASHRAE abstract archives:
ASHRAE transactions and journal papers are main sources about the UFAD systems. (More than 100 papers found)

Elsevier Literature Search Engine:
Keyword: Displacement Ventilation (26 papers found)
Keyword: UnderFloor Air Distribution (2 papers found)

Center for the Built Environment (CBE):
The Center for the Built Environment (CBE) at the UC Berkeley is a National Science Foundation Industry/University Cooperative Research Center. UFAD, as one of the HVAC systems, is the topic of the center and published many papers. The main authors are F. Bauman and T. Webster. (10 papers found)

Building Diagnostics Research Institute:
Dr. James Woods “What Real-World Experience Says About the UFAD Alternative”

The search engines and publication lists used are as follow:
- ASHRAE abstract archives (1980-1997)
- ASHRAE Bookstore
- ScienceDirect (ELSEVIER journals)
- UMI Digital Dissertations
- Wilson Abstracts

This progress report includes a general description of UFAD system, several findings, and a list of technical research and literature of the UnderFloor Air Distribution (UFAD) systems.

II. FINDINGS

2.1. General Description of Under Floor Air Distribution (UFAD) Systems (Bauman, 2003)

An underfloor air distribution (UFAD) system is an HVAC system that uses the open space (underfloor plenum) between the structural slab and the underside of a raised floor to deliver conditioned air to supply outlets located at or near floor level within the occupied zone (up to 6 ft). Since air is supplied in much closer proximity to the occupants than in conventional overhead systems, supply air temperatures must be higher (e.g., 60 ºF to 65 ºF). Usually, a task/ambient conditioning (TAC) system is used with the UFAD system to allow individuals to control thermal conditions in small and localized zones.

2.2. Three Basic Approaches of UFAD Systems (Bauman and Webster, 2001)

Currently, three types of UFAD systems are available. Bauman and Webster (2001) summarized these types in their paper. These are: 1) supply air delivered via passive floor registers and/or fan-powered terminal boxes supplied by a pressurized underfloor plenum and central air handler, 2) supply air delivered via active, locally-controlled, fan-powered registers (in the floor or workstations), supplied by a very low-pressure underfloor plenum and central air handler, and 3) supply air delivered via underfloor ducts to terminal devices or supply outlets.

III. EVALUATION OF UFAD SYSTEMS

3.1. Benefits and Barriers of UFAD Systems (Bauman, 2003)

The benefits and barriers of UFAD systems over traditional overhead air distribution systems were identified from the literature review about UFAD systems. The followings are the general benefits of a UFAD system.

1) Improved thermal comfort:
   By allowing individual occupants to control their local thermal environment
2) Improved ventilation efficiency and indoor air quality:
   By delivering the fresh supply air at floor level or near the occupant
3) Reduced energy use:
   a. Cooling energy savings from economizer operation and increased chiller COP
   b. Fan energy savings
4) Significantly reduced life-cycle building costs:
   Due to reduced expenses associated with occupant "churn," remodeling or changing interior (Addison, 2001)
5) Reduced floor-to-floor height in new construction:
   By reducing the overall height of service plenum
6) Improved productivity and health

While there are many advantages of UFAD systems over traditional overhead systems, there are still some barriers in the adoption of UFAD systems. These barriers are:

1) New and unfamiliar technology:
   Lack of familiarity can create problems throughout the entire building design, construction, and operation process, including higher cost estimates, incompatible construction methods, and incorrect building control and operation on the part of both facility managers and building occupants.
2) Lack of information and design guidelines:
   There has not previously existed a set of standardized design guidelines for use by the industry.
3) Whole-building performance:
   No whole-building energy simulation program capable of modeling a UFAD system. (Whole-building energy simulation program under EnergyPlus will be completed by 2006 by LBNL. The project is sponsored by California Energy Commission (CEC) and U.S. DOE).
4) Higher initial costs:
   Typically, a UFAD installation requires $3 to $5 per sq. ft. premium over comparable overhead systems (Daly 2002).
5) Cold feet and draft discomfort:
   Poorly designed (e.g., the close proximity of supply outlets to the occupants) and operated UFAD system can cause cold floor problem. To prevent this problem, all office floors are recommended to be carpeted.
6) Condensation and dehumidification issue:
   In humid climates, outside air must be properly dehumidified before delivering supply air to the underfloor plenum.
7) Spillage and dirt entering UFAD systems:
   There are the probability of spillage and dirt entering directly into the underfloor supply airstream. Most floor diffusers, however, have been designed with catch-basins (e.g., to hold the liquid from a typical soft drink spill).

3.2. Stratification Issues: Controlling Stratification (Bauman, 2003)

According to ASHRAE Standard 55-1992 (ASHRAE 1992), the vertical air temperature differences in interior zone is limited to 5 ºF. Recent laboratory experiments show the thermal stratification performance of UFAD systems (Webster et al. 2002a, 2002b). Figure 1 shows the impact of variations in total room air flow on stratification for swirl diffusers operation in a simulated interior space with total heat input of 18 Btu/h-ft^2 and a supply air temperature of 64 ºF. This temperature profile demonstrates the sensitivity to changes in airflow rate. According to this figure, the first profile presents the space "over-aired," while the last profile shows that the head-foot temperature difference has increased to 6.8 ºF, exceeding the limit of 5 ºF. To improve energy performance (reduce airflow) while maintaining thermal comfort (avoiding excessive stratification), the middle profile at a flow rate of 0.6 cfm/ft^2 could be a reasonable target. In this experiment, the flow rate at 0.6 cfm/ft^2 still satisfies the limitation of vertical temperature differences (5F) with 40% less air than the first profile.

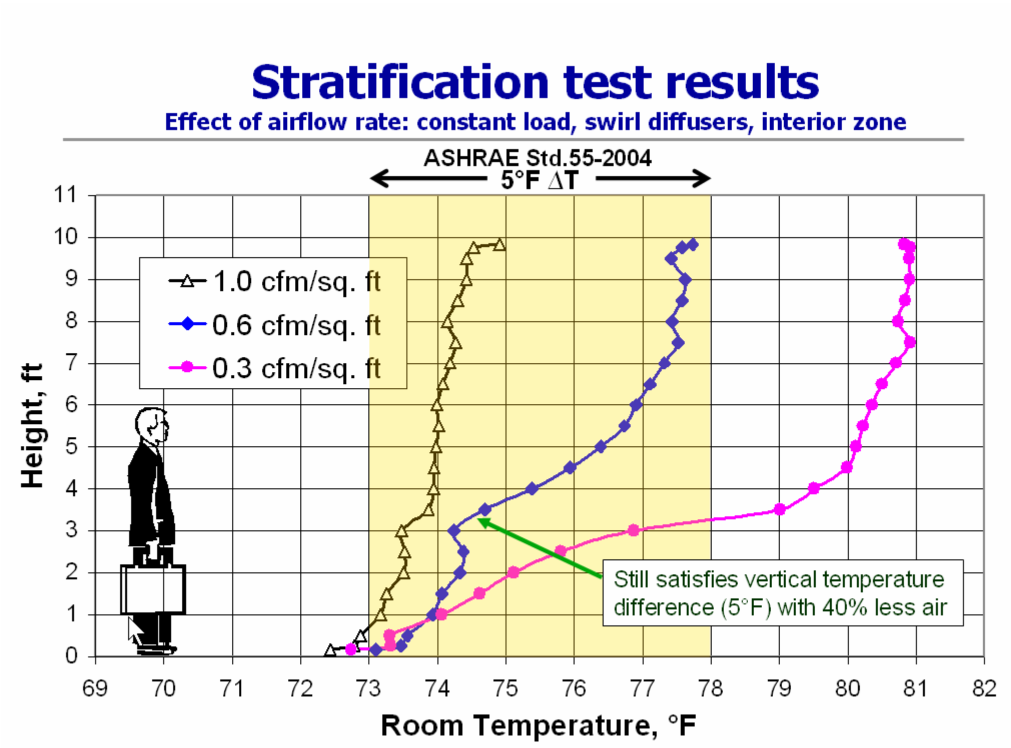

Figure 1: Effect of room airflow variation at constant heat input, swirl diffusers, interior zone. (Bauman, 2003)

3.3. CO_2 Concentration

Along with the thermal stratification issue, the issue of the CO_2 concentration in the breathing zone is discussed in some literature (Kim et al., 1992, Han et al., 1999,)

Han et al. (1999) provides the results of testing in a conference room with underfloor air-conditioning, including measurements of horizontal and vertical room air temperature distributions, CO_2 concentrations and infra-red imaging of temperature distributions over a person standing on a floor-based supply outlet.

The comparison between upward and downward ventilation systems in an office-like test space was conducted by Kim et al. (1992). The results show that changes in room CO_2 content are less affected by upward than by downward ventilation. This paper concludes that ventilation rates for removing occupant produced contaminants in the breathing zone can be low, providing supply air temperatures are less than room air temperatures.

3.4. Plenum Design Guideline (Bauman, 2003)

1) Plenum air leakage

Air leakage from a pressurized plenum may impact energy use and can impair system performance if not accounted for (see Figure 2).

2) Type of leakage
   - Leakage between floor panels and through floor electrical outlets
   - Leakage due to poor sealing and construction

3) Solutions
   - Account for leaking into occupied space in design airflow calculations
   - Careful attention to construction quality and sealing of plenum
   - Recommend leak test at end of construction

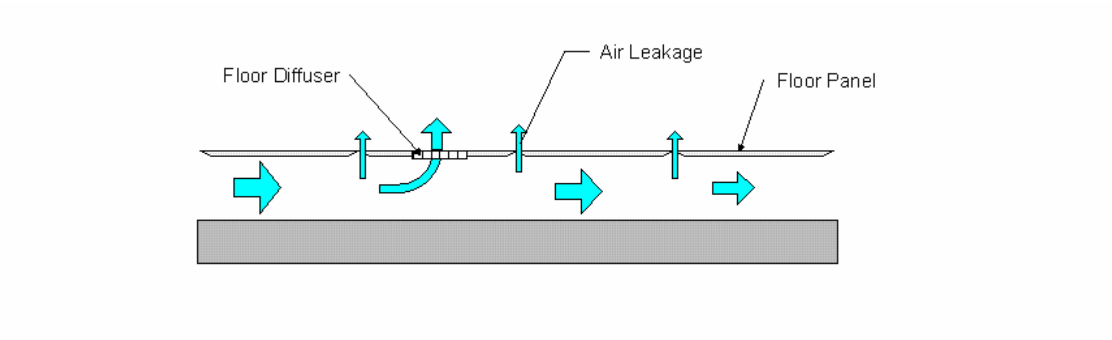

Figure 2: Plenum Air leakage (Bauman, 2003)

3.5. Task Ventilation Systems

In general, desktop task ventilation system is used along with UFAD systems. A task ventilation system permits occupant control of the temperature, flow rate, and direction of air supplied. Several authors investigate the performance of the task ventilation system. (Faulkner et al. 1993, Fisk et al., 1991, Fountain et al. 1994).

Faulkner et al. (1993) investigated the indoor airflow patterns and tobacco smoke removal efficiency of a desktop task ventilation system in a furnished experimental facility. To study indoor airflow patterns, the age of air at multiple indoor locations was measured. To study the intraroom transport of tobacco smoke particles and the efficiency of particle removal by ventilation, a cigarette was smoked mechanically in one workstation and particle concentrations were measured at multiple indoor locations, including the exhaust airstream.

Fountain et al. (1994) Fifty-four human subjects were given control of the air supply velocity from a desk fan (FAN), a floor-mounted diffuser (FMD), and a desk-mounted diffuser (DMD) at a single ambient air temperature. The subjects were asked to adjust the air movement as they pleased to make themselves comfortable. These tests encompassed the full temperature range of the "transition zone" 25.5 ºC to 28.5 ºC. Physical measurements of the environment were made and subjective votes collected, including thermal sensation, thermal preference, work area preferences, personal control preferences, and health characteristics. A model that predicts the percentage of satisfied people (the PS model) as a function of air temperature and air movement in warm conditions is proposed.

3.6. Recommendations from Experiences

Some literature provides the recommendations and existing problems from real case study buildings that have UFAD systems. Mr. Daly (2002) presents three strategies for capturing as many benefits of underfloor air distribution as possible while keeping the initial cost to a minimum: These are 1) minimize the ductwork in the plenum, 2) prevent plenum leakage, and 3) don't oversize airflows. The strategies come from experiences on seven recent projects.

a. Minimize the ductwork in the plenum:
    a. For flexibility (reconfiguration of the room) reason.
    b. To use multiple vertical shafts serving a single plenum
b. Prevent plenum leakage:
    a. Carefully seal window-wall connections to the slab at stair landings and air highways
c. Don't oversize airflows:
    a. The airflow calculation for UFAD is different with typical overhead system because the airflow calculation for UFAD needs to be broken into two parts (Two distinct room regions, occupied and unoccupied zone), while the airflow calculation for typical overhead system consider a single zone at steady state. For UFAD system, a separate energy balance equation can be written for each of the distinct zones. <u>* Currently, no validated methods exist to guide engineers assigning loads to the occupied and unoccupied zones.</u>

Dr. Woods provides an overview of recent field experience from over 60 buildings (i.e., new buildings and renewed buildings) that actually had UFAD systems. The conclusions and recommendations from his study are as follows:

a. Valid and reliable field data from UFAD systems are not available from a sufficient number of existing facilities to conclude that UFAD performance is superior to conventional air distribution systems (no demonstrable real world difference between UFAD and Conventional Air Distribution (CAD) systems in terms of system performance, economic performance and occupant complaints criteria).
b. Currently, UFAD systems provide additional alternatives that can be used by designers.

IV. SUMMARY

Extensive literature review about UFAD systems is presented. For the review, various sources and search engines were used to find the technical research and literature by using specific keywords to search for the relevant reports or browsing through the list of documents. Sources and search engines include ASHRAE abstract archives (1980-1997), Elsevier Literature Search Engine, Center for the Built Environment (CBE), Building Diagnostics Research Institute, etc.

An underfloor air distribution (UFAD) system is an HVAC system that uses the open space (underfloor plenum) between the structural slab and the underside of a raised floor to deliver conditioned air to supply outlets located at or near floor level within the occupied zone. Findings show the most commonly used three types of UFAD systems: 1) supply air delivered via passive floor registers and/or fan-powered terminal boxes supplied by a pressurized underfloor plenum and central air handler, 2) supply air delivered via active, locally-controlled, fan-powered registers (in the floor or workstations), supplied by a very low-pressure underfloor plenum and central air handler, and 3) supply air delivered via underfloor ducts to terminal devices or supply outlets.

The benefits of this system are: 1) improved thermal comfort, 2) reduced energy use, 3) reduced life-cycle building costs, 4) reduced floor-to-floor height in new construction, and 5) improved productivity and health. The barriers in the adoption of UFAD systems are: 1) still new and unfamiliar technology, 2) lack of information and design guidelines, 3) no whole-building simulation program for the system, 4) high initial costs, 5) cold feet and draft discomfort, 6) condensation and dehumidification issue, and 7) spillage and dirt entering UFAD systems.

V. REFERENCES

ASHRAE. 1992. ANSI/ASHRAE Standard 55-1992. Thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

Bauman, F. 2003. Underfloor Air Distribution (UFAD) Design Guide. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. Atlanta, GA.

Bauman, F., Webster, T. 2001. Outlook for Underfloor Air Distribution. *ASHRAE J.*, June, pp.18-25.

Daly, A. 2002. Underfloor air distribution: Lessons learned. *ASHRAE J.*, Vol. 44, No. 5, May, pp. 21-24.

Faulkner, D., Fisk, W.J., Sullivan, D.P. 1993. Indoor air flow and pollutant removal in a room with desktop ventilation. *ASHRAE Trans.*, Vol. 99, Pt. 2.

Faulkner, D., Fisk, W.J., Sullivan, D.P., Wyon, D.P. 1999. Ventilation efficiencies of desk-mounted task/ambient conditioning systems. *Indoor Air,* No. 9, pp. 273-281.

Fisk, W.J., Faulkner, D., Pih, D., McNeel, P., Bauman, F., Arens, E. 1991. Indoor air flow and pollutant removal in a room with task ventilation. *Indoor Air*, No. 3, pp. 247-262.

Fountain, M., Arens, E., de Dear, R., Bauman, F., Miura, K. 1994. Locally controlled air movement preferred in warm isothermal environments. ASHRAE Trans., Vol. 100, Pt. 2, pp. 937-952

Kim, I.G., Homma, H. 1992. Possibility for increasing ventilation efficiency with upward ventilation. *ASHRAE Technical Data Bulletin,* Vol. 8, No. 2.

Han, H., Chung, K.-S., Jang, K.-J. 1999. Thermal and ventilation characteristics in a room with underfloor air-conditioning system. *Proc. Indoor Air '99*, Edinburgh, Scotland.

Webster, T., Bauman, F., Reese, J. 2002-a. Underfloor air distribution: Thermal stratification. *ASHRAE J.*, Vol. 44, No. 5, May, pp. 28-36.

Webster, T., Bauman, F., Reese, J., Shi, M. 2002-b. Thermal stratification performance of underfloor air distribution (UFAD) systems. *Proc. Indoor Air 2002,* Monterey, CA, 30 June - 5 July 2002.

VI. ANNOTATED BIBLIOGRAPHY

Addison, M., Nall, D. 2001. Cooling via underfloor air distribution: Current design issues and analysis options. From: *Cooling Frontiers: The Advanced Edge of Cooling Research and Applications in the Built Environment*. College of Architecture and Environmental Design, Arizona State University.

This paper provides a brief description of the significant features, potential advantages, and design issues associated with underfloor air distribution. The current and emerging whole building energy analysis and HVAC design simulation tools were described.

Potential advantages of UFAD:
1) Significantly reduced building life-cycle costs due to reduced expense associated with occupant "churn"
2) Significant life-cycle savings due to improved occupant satisfaction and productivity via improved thermal comfort and indoor air quality
3) Reduced energy use and cost

Akimoto, T., Nobe, T., Takebayashi, Y. 1995. Experimental study on the floor-supply displacement ventilation system. *ASHRAE Trans.*, 101(2).

This paper presents results from a research project to investigate the effects of a floor-supply displacement ventilation system with practical indoor heat loads. The experiments were performed in an experimental chamber ($35.2m^2$) located in a controlled environment chamber. Temperature distributions were measured at seven heights throughout the experimental chamber for each test condition. Data were analyzed to observe thermal stratification as affected by lighting, occupants, and heat loads (personal computers), and its disruption caused by walking and change of air volume. In addition, air flow characteristics and ventilation efficiencies were investigated using a smoke machine, tobacco smoke, dust for industrial testing, and a tracer gas (CO_2) step-up procedure.

Arens, E.A., Bauman, F., Johnston, L., Zhang, H. 1991. Testing of localized ventilation systems in a new controlled environment chamber. *Indoor Air*, No. 3, pp. 263-281.

This paper describes tests of thermal comfort and air distribution performance of two relatively new occupant-controlled localized ventilation (also called task ventilation) systems. The tests were performed in a new controlled environment chamber (CEC) having capabilities for detailed studies of space conditioning and thermal comfort in office environments. The results show that temperature differences in the range of 1-2.5 ºC were observed between adjacent workstations and local air velocity in the vicinity of outlets could exceed 3 m/s, which can cause draft discomfort in this region. Although these could violate could violate existing comfort standards, it is recommended that the standards grant exceptions to such systems.

Bauman, F.S., Johnston, L., Zhang, H., Arens, E. 1991a. Performance testing of a floor-based, occupant-controlled office ventilation system. *ASHRAE Trans.*, Vol. 97, Pt. 1.

This paper presents the results of experiments in a controlled chamber configured to resemble an office with modular partitions, investigating the effects of supply volume, location, and direction, supply/return temperature difference, heat load density and workstation size and layout. Using ASHRAE test methods current in 1991, overhead supply systems scored a higher performance rating. This paper concludes the comfort benefits of occupant-control over the local environment are not adequately addressed in existing performance and comfort standards.

Bauman, F., Arens, E.A., Tanabe, S., Zhang, H., Baharlo, A. 1995. Testing and optimizing the performance of a floor-based task conditioning system. *Energy and Buildings* 22, pp. 173-186.

Laboratory measurements were made to investigate the performance of an occupant-controlled floor-based task conditioning system. For the experiments, a controlled environmental chamber which is configured to resemble a modern office space was used. Detailed tests were conducted to study the effect of supply volume, supply temperature, supply direction and heat levels in the general office space. It was found that: 1) overall performance of the floor-based system resembled that of displacement system, 2) it is recommended to reduce the maximum airflow rate of the floor supply module below 190cfm, and 3) by controlling supply volume, the floor-based system can be operated to maintain acceptable thermal comfort.

Bauman, F. 1999. Giving occupants what they want: Guidelines for implementing personal environmental control in your building. *Center for the Built Environment,* University of California, Berkeley, April.

This paper includes concise descriptions of the principles of an underfloor TAC system, potential benefits and guidelines on how to achieve them, and ongoing work addressing current barriers (real and perceived) to widespread use of the technology. It incorporates recent research findings and outlines areas for future study (from UFAD Design Guide by Bauman).

Bauman, F., Webster, T. 2001. Outlook for Underfloor Air Distribution. *ASHRAE J.*, June, pp. 18-25.

This paper offers a system description, discusses the benefits of underfloor technology, and lists and discusses the "technology needs" or the current barriers to its widespread adoption (from UFAD Design Guide by Bauman).

Bauman, F., Pecora, P., Webster, T. 1999a. How low can you go? Airflow performance of low-height underfloor plenums. *Center for the Built Environment*, University of California, Berkeley, October.

This comprehensive report summarizes results from full-scale testing of pressurized underfloor plenum configurations and their influence on the uniform distribution of supply air to floor grilles. Useful technical recommendations are cited such as minimum plenum heights, the effect of obstructions or removing floor panels, and plenum inlet conditions (from UFAD Design Guide by Bauman).

Daly, A. 2002. Underfloor air distribution: Lessons learned. *ASHRAE J*., Vol. 44, No. 5, May, pp. 21-24.

This paper presents three strategies for capturing as many benefits of underfloor air distribution as possible while keeping the initial cost to a minimum. They are: 1) minimize the ductwork in the plenum, 2) prevent plenum leakage, and 3) don't oversize airflows. The strategies come from experiences on seven recent projects.

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de Dear, R., Brager, G.S. 1998. Developing an adaptive model of thermal comfort and preference. *ASHRAE Trans.*, Vol. 104, Pt. 1.

Under the hypothesis that contextual factors and past thermal history modify building occupants' thermal expectations and preferences, a worldwide thermal comfort database was compiled examining thermal sensation, acceptability and preference from observations in 160 buildings. The results formed the basis of a proposal for a variable indoor temperature standard.

Faulkner, D., Fisk, W.J., Sullivan, D.P. 1993. Indoor air flow and pollutant removal in a room with desktop ventilation. *ASHRAE Trans.*, Vol. 99, Pt. 2.

The authors investigated the indoor airflow patterns and tobacco smoke removal efficiency of a desktop task ventilation system in a furnished experimental facility. The task ventilation system permits occupant control of the temperature, flow rate, and direction of air supplied through two desk-mounted supply nozzles. To study indoor airflow patterns, the age of air at multiple indoor locations was measured. To study the intraroom transport of tobacco smoke particles and the efficiency of particle removal by ventilation, a cigarette was smoked mechanically in one workstation and particle

concentrations were measured at multiple indoor locations, including the exhaust airstream.

Faulkner, D., Fisk, W.J., Sullivan, D.P., Wyon, D.P. 1999. Ventilation efficiencies of desk-mounted task/ambient conditioning systems. *Indoor Air*, No. 9, pp. 273-281.

Outlines required outdoor air content, supply airflow rate and direction for optimum values of air exchange effectiveness and pollution removal efficiency in the breathing zone of heated manikins with desk-mounted air outlets (from UFAD Design Guide by Bauman).

Fisk, W.J., Faulkner, D., Pih, D., McNeel, P., Bauman, F., Arens, E. 1991. Indoor air flow and pollutant removal in a room with task ventilation. *Indoor Air*, No. 3, pp. 247-262.

The performance of a task ventilation system was studied. Occupants could control the flow rate and direction of air supplied to their work space through four floor-mounted supply grills.

Fountain, M., Arens, E., de Dear, R., Bauman, F., Miura, K. 1994. Locally controlled air movement preferred in warm isothermal environments. ASHRAE Trans., Vol. 100, Pt. 2, pp. 937-952

Fifty-four human subjects were given control of the air supply velocity from a desk fan (FAN), a floor-mounted diffuser (FMD), and a desk-mounted diffuser (DMD) at a single ambient air temperature. The subjects were asked to adjust the air movement as they pleased to make themselves comfortable. These tests encompassed the full temperature range of the "transition zone" 25.5 ºC to 28.5 ºC. Physical measurements of the environment were made and subjective votes collected, including thermal sensation, thermal preference, work area preferences, personal control preferences, and health characteristics. A model that predicts the percentage of satisfied people (the PS model) as a function of air temperature and air movement in warm conditions is proposed.

Fujita, H., Sakai, K. 1996. Room air temperature profiles in underfloor air distribution system. *Proceedings, Indoor Air*, 1996.

The proposed model for estimating room air temperature profiles and flow patterns indicates the significant relationship between heat- and temperature-profiles, and the need for accurate measurements of heat loads (from UFAD Design Guide by Bauman).

Fukao, H., Oguro, M., Hiwatashi, K., Ichihara, M. 1996. Environment evaluation in an office with floor-based air-conditioning system in an office building. *Proc. 5th International Conference on Air Distribution in Rooms, ROOMVENT '96*, Yokohama, Japan, 1996.

This paper presents the results of field measurements and a survey questionnaire concerning the thermal environment in an office building employing both floor- and ceiling-based systems. Significant differences were observed only for air particle concentrations. Included is a graphical analysis of thermal sensations over different parts of the human body (from UFAD Design Guide by Bauman).

Genter, R.E. 1989. Air distribution for raised floor offices. *ASHRAE Trans*., Vol. 95, Pt. 2.

This paper presents an individual approach to the design of air distribution for office buildings using the plenum under a raised floor. It details the mathematical manipulations of modifying a standard variable air volume (VAV) design into an underfloor air supply system in the logic sequence developed in accomplishing the building HVAC design. Example problems and diagrams illustrate the effect of the major influencing factors (from UFAD Design Guide by Bauman).

GSA. 1992. GSA access floor study. U.S. General Services Administration, Washington, D.C., E.B. Commission No. 7211-911C, September 10.

This report presents a detailed 25-year Present Value Analysis and study of the use of access floor systems in GSA office facilities with the aim of determining the best value for open plan offices. Useful and comprehensive for comparative means, in addition to studying three different access floor systems, the analysis considers both steel- and concrete-framed building structures (from UFAD Design Guide by Bauman).

Hanzawa, H., Nagasawa, Y. 1990. Thermal comfort with underfloor air-conditioning systems. *ASHRAE Trans*., Vol. 96, Pt. 2.

This paper presents the results of experiments carried out in a test chamber with human occupants measuring the subjective perception of supply air flow from a floor outlet. Conclusions of a low draft risk with underfloor air systems are based on the draft charts of Fanger et al (1988) (from UFAD Design Guide by Bauman).

Hanzawa, H., Nagasawa, Y., Mortyama, T. 1993. Field measurements of thermal comfort in occupied zones of buildings installed with under-floor air-conditioning systems. Proceedings, Room Air Convection and Ventilation Effectiveness, ASHRAE, 1993.

From field measurements of two office buildings with underfloor air conditioning systems and looking at room air temperatures, air velocities and responses to questionnaires on air movement and drafts, this paper concludes that internal conditions are comfortable according to standard thermal indexes (from UFAD Design Guide by Bauman).

Hanzawa, H., Higuchi, M. 1996. Air flow distribution in a low-height underfloor air distribution plenum of an air conditioning system. *AIJ J. Technological Design*, No.3, pp 200-205, December.

This paper presents the results of experiments with scale models of underfloor plenums, investigating the characteristics, observed problems, and possible countermeasures of air-flow within low-height plenums. Experimental parameters included varying air supply inlet number and type, obstacles and guide vanes within the plenum. In conclusion, low height pressurized plenums are found to be feasible within an optimum range of floor area per outlet ratio (from UFAD Design Guide by Bauman).

Han, H., Chung, K.-S., Jang, K.-J. 1999. Thermal and ventilation characteristics in a room with underfloor air-conditioning system. *Proc. Indoor Air '99*, Edinburgh, Scotland.

This paper outlines the results of testing in a conference room with underfloor air-conditioning, including measurements of horizontal and vertical room air temperature distributions, CO_2 concentrations and infra-red imaging of temperature distributions over a person standing on a floor-based supply outlet (from UFAD Design Guide by Bauman).

Hedge, A., Michael, A., Parmelee, S. 1992. Reactions of facilities managers and office workers to underfloor task air ventilation. *J. Arch. Planning and Res*.

This paper presents results from field study surveys of user reaction to underfloor systems as compared to overhead ventilation in their previous workplaces, the 1st survey of this kind in the U.S. Results are presented with consideration of human factors and ergonomics with discussions as to why occupant control is often voted a primary benefit, yet rarely exercised (from UFAD Design Guide by Bauman).

Heinemeier, K.E., Schiller, G.E., Benton, C.C. 1990. Task conditioning for the workplace: issues and challenges. *ASHRAE Trans.*, Vol. 96, Pt. 2.

This paper states that underfloor air distribution is now being used in open-plan offices. Supplying conditioned air from the floor provides the opportunity for localized conditioning with individual control, known as 'task conditioning'. It indicates that this environmental control strategy can be viewed as encompassing a combination of several more conventional strategies, including occupant-defined comfort, use of occupancy-sensors, temperature stratification, increased ventilation efficiency and thermal storage. It gives an overview of task conditioning in offices, describing existing system types and the most common applications. It outlines the current state of understanding concerning the comfort and energy effects of these systems and identifies important questions that must be addressed to complete the understanding of this strategy.

Heinemeier, K.E., Brager, G., Benton, C., Bauman, F., Arens, E. 1991. Task/ambient conditioning systems in open-plan offices: assessment of a new

technology. ***Center for Environmental Design Research,*** **University of California, Berkeley, September.**

This paper contains an early commentary on the level of knowledge regarding task/ambient conditioning and identification of specific issues needing further research at the start of the 90s. The detailed analysis of system principles, strategies and the affect of task/ambient systems on comfort and energy use, remain relevant to present day applications (from UFAD Design Guide by Bauman).

Houghton, D. 1995. Turning air conditioning on its head: underfloor air distribution offers flexibility, comfort, and efficiency. ***E Source Tech Update TU-95-8,*** **E Source, Inc., Boulder, CO, August, 16 pp.**

A good general summary of underfloor air distribution systems, this paper provides an objective overview of the technology, including both the benefits and potential drawbacks, and gives advice on how to avoid them. Sections include an outline of different system types, economic appraisal, market trends, products and manufacturers, all well as illustrations with graphics and photographs (from UFAD Design Guide by Bauman).

Int-Hout, D. 2001. Pressurized Plenum Access Floor - Design Manual. ***Carrier*****, November.**

An overview of issues and design considerations, this manual includes history, basic concepts, advantages of the system, design considerations, design challenges, a summary of current research and the Carrier approach (from UFAD Design Guide by Bauman).

Ito, H., Nakahara, N. 1993. Simplified calculation model of room air temperature profile in underfloor air-conditioning system. Proceedings, Room Air Convection and Ventilation Effectiveness, ASHRAE 1993.

Using this simplified calculation model, a close correlation between calculated and measured vertical temperature distributions indicated a level of accuracy suitable for use in HVAC design applications. These variations in room dimensions have little influence on room air temperature profiles (from UFAD Design Guide by Bauman).

Iwamoto, S. 1999. A study on numerical prediction method of indoor environment including human body. Proc. International Conference on Air Distribution in Rooms, ROOMVENT '99.

The author compares two numerical methods of calculating a three-dimensional model of air flow and temperature around an occupant's body, based on a curvilinear coordinate system. The detailed predictions possible with such models are necessary when evaluating personal (task-ambient) conditioning installations (from UFAD Design Guide by Bauman).

Kim, I.G., Homma, H. 1992. Possibility for increasing ventilation efficiency with upward ventilation. *ASHRAE Technical Data Bulletin*, Vol. 8, No. 2.

The results of experiments comparing upward and downward ventilation systems in an office-like test space with human occupants indicate changes in room CO_2 content are less affected by upward than by downward ventilation. This paper concludes that ventilation rates for removing occupant produced contaminants in the breathing zone can be low, providing supply air temperatures are less than room air temperatures (from UFAD Design Guide by Bauman).

Kim, I.G., Homma, H. 1992. Distribution and ventilation efficiency of CO2 produced by occupants in upward and downward ventilated rooms. *ASHRAE Technical Data Bulletin*, Vol. 8, No. 2.

This paper expands on the results of the previous experiments by the authors (see reference above) to include a more detailed analysis of factors influencing efficient removal of CO_2 content from a room, such as occupant produced metabolic heat and CO_2 concentration stratification (from UFAD Design Guide by Bauman).

Kim, Y., Lee, K., Cho, H. 2001. Experimental Study of Flow Characteristics of a Diffuser for Under Floor Air-Conditioning System. *ASHRAE Trans*., Vol. 107, Pt. 1.

In this study, a new diffuser for the underfloor air conditioning system is developed and flow characteristics for isothermal conditions are studied. The new diffuser consists of two sections: 1) an internal section for generating swirl flow and 2) an edge section for vertical flow. It concludes that the new diffuser has desirable characteristics (from UFAD Design Guide by Bauman).

Loudermilk, K. 1999. Underfloor air distribution solutions for open office applications. A*SHRAE Trans*., Vol. 105, Pt. 1.

This paper outlines underfloor air distribution systems design and operation criteria for optimizing performance and minimizing costs. It includes a useful description of temperature distributions and zone differentiation within a room, and tables for sensible heat gain analysis (from UFAD Design Guide by Bauman).

Matsunawa, K., Iizuka, H., Tanabe, S. 1995. Development and application of an underfloor air conditioning system with improved outlets for a smart building in Tokyo. *ASHRAE Trans*., Vol. 101, Pt. 2.

This study investigated an underfloor air conditioning system developed for a high technology “smart” building in Tokyo. Experiments and numerical simulations were conducted before the introduction of the system to calculate the thermal comfort and energy savings. The research results were compared to the ASHRAE Standard 55-92, which includes recommendations of thermal comfort requirements, and showed that the underfloor air conditioning system implemented with the improved type of outlet provided the indoor environment quality that meets the standard.

McCarry, B.T. 1995. Underfloor air distribution systems: benefits and when to use the system in building design. *ASHRAE Trans*., 1995, Vol. 101, Pt.2.

This paper addresses the optimum context and application for underfloor air distribution systems. Illustrated with reference to three buildings in Vancouver, Canada, the discussion addresses design, mechanical systems issues, potential benefits and where the use of an underfloor air system is, or is not, appropriate (from UFAD Design Guide by Bauman).

McCarry, B.T. 1998. Innovative underfloor system. *ASHRAE J.*, March,

This is a case study of a library building in Vancouver, Canada, featuring a low-pressure underfloor air distribution system. The financial and operational success of the system exemplifies the potential for underfloor applications outside the genre of office buildings (from UFAD Design Guide by Bauman).

Melikov, A.K., Cermak, R., Majer, M. 2002. Personalized ventilation: Evaluation of different air terminal devices. *Energy and Buildings*, Vol. 34, pp. 829-836.

A comparative study of five different supply Air Terminal Devices (ATDs) was conducted. Five systems were developed, tested and compared to see each system's performance of Personalized Ventilation (PV) that depends mainly on the supply air terminal devices. A typical office workplace and a manikin were used for simulations. The results showed that PV may decrease the occupant dissatisfaction of the air quality significantly. But, better ATD that will ensure more efficient distribution and less mixing of the personalized air with the polluted room air needs to be developed.

Milla, F. A. 2005. Underfloor Ventilation Applied to Low Energy NatVent Buildings. Presentation in 2005 ASHRAE Winter Meeting, Orlando, FL.

The underfloor ventilation system applied to low energy naturally ventilated buildings is discussed. The author introduces a natural ventilated building, mechanical ventilated building and hybrid (i.e. natural and mechanical ventilated building) building. The findings and conclusions are 1) displacement ventilation follows natural air flow patterns, 2) displacement system requires lower air change rates, 3) new building with the system provides opportunity to reduce HVAC systems but still needs attention to IAQ, 4) combined natural ventilation and mechanical ventilation with or without cooling/dehumidification can achieve comfort, energy savings and cost savings.

Nakahara, N., Ito, H. 1993a. Prediction of mixing energy loss in a simultaneously heated and cooled room: part 1 -- experimental analyses of factorial effects. *ASHRAE Trans.*, Vol. 99, Pt. 1, pp. 100-114.

This paper deals with the issue of mixing energy loss, which is affected by many design and control factors of air distribution systems. An analysis was performed for a simulated full-scale office room using a number of experiments. The study discovered the significance and effect of various design and control factors on the mixing energy loss. Also, strategies that are useful for design and control of air distribution systems were developed, preventing the mixing energy loss and keeping a comfortable indoor condition.

Nakahara, N., Ito, H. 1993b. Prediction of mixing energy loss in a simultaneously heated and cooled room: part 2 -- simulation analyses on seasonal loss. *ASHRAE Trans.*, Vol. 99, Pt. 1, pp. 115-128.

This study is the second part of previous research (see reference above), dealing with simulation analysis on seasonal loss. Mixing energy Loss (ML) was estimated using regressive models which have been developed based on the experimental results of Part 1. Dynamic heat-loss calculation method, which includes a regressive model of mixing energy loss, was used for case studies to estimate the seasonal properties of heat that are supplied to a space. Factors on the seasonal heat consumption were also discussed.

Sandberg, M., Blomqvist, C. 1989. Displacement ventilation systems in office rooms. *ASHRAE Trans.*, Vol. 95, Part 2.

This paper summarizes the measurement results performed in an office room and shows the existence of limitations of displacement ventilation. There are specific design requirements for supply air terminals and restrictions on the maximum heat load due to the temperature gradient. The concentration in the breathing zone is the same as with traditional mixing systems when the normal flow rates are supplied to office rooms.

Schiller, G., Arens, E., Bauman, F., Benton, C., Fountain, M., Doherty, T. 1988. A field study of thermal environments and comfort in office buildings. *ASHRAE Trans*., Vol. 94, Pt. 2.

This paper presents findings from a study of occupants' comfort and environmental conditions in ten office buildings located in the San Francisco Bay area.

Seem, J.E., Braun, J. 1992. The impact of personal environmental control on building energy use. *ASHRAE Trans*., Vol. 98, Pt. 1.

This paper compares the energy use characteristics of personal environmental control (PEC) systems and conventional HVAC systems, concluding that the benefits of increased staff productivity outweigh costs in other areas (from UFAD Design Guide by Bauman).

Shinkai, K., Kasuya, A., Kato, M. 2000. Performance Evaluation of Floor Thermal Storage System. *ASHRAE Trans*, Vol. 106, Pt. 1.

This paper describes results regarding the peak shaving by a floor thermal storage system in designing the air conditioning system for an officially recognized "environmentally conscious building No. 1" for the Osaka Gas Company (from UFAD Design Guide by Bauman).

Shute, R.W. 1992. Integrated access floor HVAC. *ASHRAE Trans*, Vol. 98, Pt. 1.

An overview of the evolution of floor based HVAC is presented as a case study of the six-year development period of an office project in Toronto, Canada. This paper discusses in detail two variations each of compartmentalized and centralized systems, concluding with comprehensive design guidelines and constructional coordination issues based on the experiences of the office project (from UFAD Design Guide by Bauman).

Sodec, F., Craig, R. 1990. The underfloor air supply system -- the European experience. *ASHRAE Trans.*, Vol. 96, Part 2.

The underfloor air distribution system is applied to offices. Results indicate that the air pollution of the underfloor air distribution system in the occupied zone is lower compared to the conventional air supply systems. Individuals received more fresh air directly and the installation cost of the underfloor air distribution system is up to 10% less.

Spoormaker, H.J. 1990. Low-pressure underfloor HVAC system. *ASHRAE Trans,* Vol. 96, Part 2.

This paper presents a case study of the development and operation of a low-pressure underfloor air conditioning system as installed in a South African office building in the early '80s. It includes useful classifications of levels of flexibility, durability, reliability and maintainability for HVAC systems, and a schematic description of a low-pressure underfloor HVAC system (from UFAD Design Guide by Bauman).

Svensson, A.G.L. 1989. "Nordic experiences of displacement ventilation systems." ASHRAE *Trans*, Vol. 95, Part 2.

This paper points out that ventilation systems utilizing the displacement principle currently have 25% of the market in new office buildings in Nordic countries, and discusses the current state of displacement systems with regard to air exchange efficiency, ventilation efficiency and thermal comfort. Also, it discusses trends in the development of the systems and predicts a bright future for this technique of supplying air at low velocity.

Trox. 1997. Building design optimization with underfloor air distribution in the San Francisco area" *Trox USA*, Alpharetta, GA.

One of the most comprehensive collections of papers on underfloor air distribution available, this paper provides the latest information and guidelines on many aspects including office space optimization, comparisons of overhead and underfloor systems, load analysis, design considerations and a review of competitors' systems. Each topic is illustrated with test results, calculations (e.g. space heat gain), charts (e.g. psychrometric) and a process analysis (from UFAD Design Guide by Bauman).

Webster, T., Ring, E., Bauman, F. 2000. Supply fan energy use in pressurized underfloor plenum systems. *Center for the Built Environment*, University of California, Berkeley, CA.

This preliminary study examines the impact of various design assumptions on the fan energy consumption of pressurized underfloor plenum systems compared to traditional overhead constant-air-volume and variable-air-volume systems (from UFAD Design Guide by Bauman).

Webster, T., Bauman, F., Reese, J. 2002-a. Underfloor air distribution: Thermal stratification. *ASHRAE J*., Vol. 44, No. 5, May, pp. 28-36.

This article describes the idea of stratification, whose control and optimization is crucial for system design of underfloor systems. This article focuses on practical implications of room air stratification testing results for the control and operation of constant air volume and variable air volume UFAD systems (from UFAD Design Guide by Bauman).

Webster, T., Bauman, F., Reese, J., Shi, M. 2002-b. Thermal stratification performance of underfloor air distribution (UFAD) systems. *Proc. Indoor Air 2002*, Monterey, CA, 30 June - 5 July 2002.

This paper presents tests to "determine the impact of room airflow and supply air temperature (SAT) on the thermal stratification in interior spaces, and the effect of blinds in perimeter spaces for UFAD systems." Results are outlined and discussed (from UFAD Design Guide by Bauman).

Wood, J.E. 2005 Evaluation of the Performance of Underfloor Air Distribution Systems. Presentation in 2005 ASHRAE Winter Meeting, Orlando, FL.

This study identifies and discusses issues, resolutions, findings, and conclusions about UFAD systems revealed from 7 sites visits and 15 design reviews in the U.S. Followings are the conclusions from this study.

1. There are types of buildings suitable or not suitable for UFAD system.
2. Two fundamental performance issues must be addressed
    1) The slabs have significant thermal inertia that affect control strategies and energy efficiency
    2) Plenum air leakage must be minimized to within 10% of supply airflow
3. Plenum safety issues must be addressed (i.e., water detection and drainage, Early smoke detection in the plenum, Emergency Power Off station, Structural damage or collapse, Physical protection of occupants when panels are open)

Wyon, D.P., Sandberg, M. 1990. Thermal manikin prediction of discomfort due to displacement ventilation. *ASHRAE Trans*, Vol. 96, Pt. 1.

This study investigates the problems caused by the displacement ventilation systems in offices. People sitting in the offices felt uncomfortable due to cold air on their legs and feet and heat discomfort at head height. Results from an empirical study using the thermal manikin system VOLTMAN are shown as diagrams and tables. Also, suggestions are provided for improving thermal comfort with displacement ventilation.

Yuan, X., Chen, Q., Glicksman, L. 1998. A critical review of displacement ventilation. *ASHRAE Trans*, 104(1).

This paper examines the performance of displacement ventilation in view of several aspects such as temperature distribution, flow distribution, contaminant distribution, comfort, energy and cost analysis, and design guidelines. Findings from the research were summarized and a recommendation was introduced that the design guidelines of displacement ventilation that have been developed for Scandinavian countries need to be expanded to U.S. buildings.

Yuan, X., Chen, Q., Glicksman, L. 1999. Performance evaluation and design guidelines for displacement ventilation. *ASHRAE Trans*, 105(1).

This paper investigates the performance of traditional displacement systems for various spaces under thermal and flow boundary conditions. Guidelines for designing displacement ventilation applied to U.S. buildings are presented based on research results obtained from Scandinavian countries.